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# Discontinuous PWM for Online Condition Monitoring of SiC Power Modules

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**Abstract**— This paper presents the utilization of discontinuous PWM modulation for the condition monitoring of SiC power MOSFETs switching at high switching frequencies in a three-phase inverter prototype. Due to the settling time imposed by the monitoring system, accurate measurements require low switching frequency and high modulation indexes when monitoring. To overcome these limitations, a discontinuous PWM modulation strategy is proposed. This way, the monitored device does not switch during certain time, and hence the accuracy of the measurements is not compromised. The effect of the alteration of the modulation is analyzed in terms of power losses and current ripple, comparing the traditional with the proposed modulation. Moreover, online monitoring results performed in a SiC-based inverter prototype in different operating points are presented. An  $R_{DS}$ -based thermal model is presented in order to estimate online the junction temperature.

## I. INTRODUCTION

Nowadays, the integration of wide-bandgap (WBG) semiconductor devices in power electronics industry is experiencing a huge increase. The improved properties offered by materials such as SiC and GaN compared with those of Si [1], like higher electric field, electron velocity and high temperature operation, allow to obtain better semiconductor devices that lead to more efficient and smaller power electronic converters. Regarding SiC devices, their enhanced performance has favoured its industrial introduction, especially in high-power applications. In these applications, such as traction or renewable energy generation, the improvements in terms of the reduction of volume and increase of switching frequency and efficiency are even more evident [2], [3], [4].

However, the lack of maturity of these devices and the short experience with them in in-field conditions cause uncertainty regarding their long-term degradation. In order to overcome these issues, condition monitoring has been proposed as a way to predict failures and enhance the reliability of power electronics systems [5]. A recent survey among industry experts recognised condition monitoring as a key method to achieve a higher reliability in power converters [6]. There, power modules and electrolytic capacitors were considered as the components most susceptible to failure, while condition monitoring was identified as an interesting trend to improve system reliability. By employing condition monitoring, maintenance can be schedule when required. Moreover, active

thermal control techniques can be implemented in order to reduce degradation and extend the useful lifetime [7].

Package-related failures are considered the limiting factor to increase the lifetime of power modules [8]. For IGBT power modules, bond-wire and solder joints degradation are the two most relevant failure mechanisms [9]. Both are caused by the thermomechanical stress caused by the power losses generated in the semiconductors [10]. Since the packaging employed for IGBTs is similar to that of SiC power modules, similar wear-out failures can be expected. Moreover, a comparison between the fatigue stress in a Si and a SiC power module was presented in [11] for the same electrical ratings and temperature profiles. The study concluded that a higher stress and therefore lower lifetimes is expected in SiC power modules due to the mechanical properties of SiC. A number of condition monitoring techniques have been presented in order to evaluate the state-of-health of the semiconductors [12]. However, it is often difficult to diagnose the root-cause of degradation, since different failure mechanism have the same failure effect.

Condition monitoring usually requires dedicated circuits, which have to reduce noise and measurement errors [13], [14]. Furthermore, the monitoring system is usually device-specific, since the damage-sensitive monitored parameters are influenced by the packaging and the internal layout of the module. Moreover, the monitoring circuit must be easily integrable in the converter, in order to be implemented in an industrial product [15]. This implies that the system must be able to perform online measurements without interfering on the regular operation of the converter. Furthermore, the monitoring system must not compromise the overall system reliability. Although several monitoring systems have been proposed in the literature, only few of them have been tested in in-field conditions [16], [17], [18], [19].

For those single-chip power modules with an auxiliary source available for control purposes, it was proposed in [20] a technique to predict the junction temperature of the Device Under Test (DUT) independently of the degradation on the bond wires. The mentioned technique consists in the use of the on-state resistance as a Temperature Sensitive Electrical Parameter (TSEP) [14], [21]. This is obtained by monitoring the on-state voltage between the drain and auxiliary source

TABLE I  
PROTOTYPE SPECIFICATIONS.

| Three Phase Inverter |           |              |
|----------------------|-----------|--------------|
| Power Module         | Wolfspeed | CCS050M12CM2 |
| DC-Link Voltage      |           | 300 V        |
| DC-Link Capacitance  |           | 49 $\mu$ F   |
| $L_{Filter}$         |           | 2.4 mH       |
| $R_{Load}$           |           | 40 $\Omega$  |
| Output Frequency     |           | 50 Hz        |

$V_{DS_{aux}}$  and the drain current  $I_D$ . However, the monitoring requires certain minimum on-state times in order to work properly. This fact limits the maximum switching frequency that can be achieved by the DUT, which in turn limits the potential benefits of SiC. Similar issues have been found in other publications [18], [22].

To overcome the above limitation, a discontinuous modulation during a fundamental period of the modulation signal could be implemented for monitoring. The use of discontinuous pulse-width modulation (DPWM) has already been proposed for different purposes, being it popular due to the reduction of switching losses. This modulation has been employed to reduce thermal stress and enhance the lifetime [23], [24], [25] or to achieve higher efficiencies or power densities [26], [27], [28].

In this paper, the use of a discontinuous modulation for the monitoring of power semiconductors in inverter systems is proposed. This way, the measurements can be carried out during normal operation of the converter without interruption for monitoring purposes. This is mandatory in high power SiC-based converters, which take advantage of the high switching frequency capabilities of SiC devices. The remainder of the paper is arranged as follows. In Section II, the set-up employed to perform the tests is described, along with the monitoring system and the DUT. Section III shows the limitation of conventional monitoring system in comparison with the proposed one. Section IV shows the experimental results at different operating points. Section V finalizes the paper with conclusions.

## II. EXPERIMENTAL SET-UP

### A. Prototype Specifications

In order to present the problem of monitoring at high switching frequency, a SiC-based converter prototype has been developed. In Figure 1(a), a functional diagram of the prototype is shown, along with a photograph of the set-up in Figure 1(b). Concretely, it consists of a three-phase inverter, in which the Condition-Monitoring System (CMS), whose details are described below, is implemented on one of the active switches.

The power module employed is a six-pack 1200-V/50-A MOSFET module, which consists on three half-bridge branches in parallel. The module is mounted on a forced air-cooled heatsink. For the control of the converter and the CMS, a digital microcontroller is employed along with commercial SiC gate drivers. Moreover, a DC-Link is sized in order to

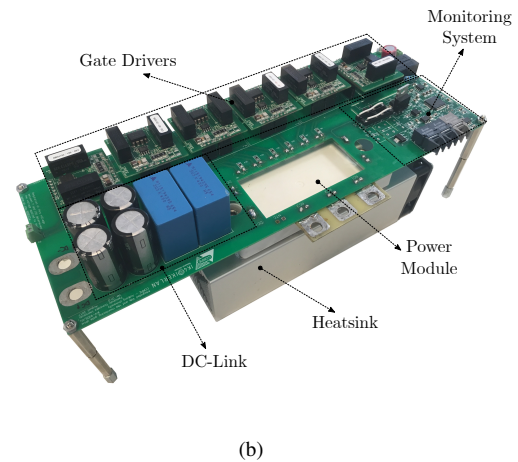
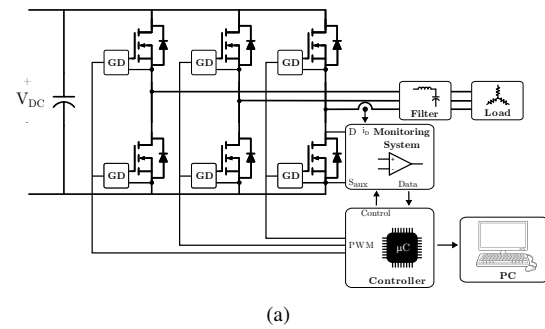


Fig. 1. Experimental set-up: (a) Functional diagram of the components of the system. (b) Photograph of the prototype.

meet the desired performance. In Table I, the specifications of the prototype are collected.

### B. Condition Monitoring System

A condition-monitoring circuit is integrated in the described platform in order to estimate the junction temperature of the DUT. Several publications have proved that the on-state resistance  $R_{DS}$  is a valid TSEP for SiC MOSFETs [14], [21], [29]. Hence, it could be employed for the online estimation of the junction temperature. This way, if an increase of the thermal resistance of the module occurs as a consequence of the solder degradation, the resulting higher junction temperature can be predicted.

In Figure 2(a), the internal layout of the employed module is presented. In order to determine its on-state resistance, the voltage between Drain and Source  $V_{DS}$  and the drain current  $I_D$  of the DUT have to be measured. However, if the monitoring is performed between the AC and DC- terminals of the module, it comprises the voltage drop in the power source bond wires. Hence, the measurement would be sensitive to bond wire failures [30]. To avoid the mix-up of failures, the monitoring is carried out between the drain  $D$  and auxiliary source  $S_{aux}$  of the DUT. This way, the voltage drop in the power source bond wires does not influence the measurement.

The monitoring of  $V_{DS}$  is carried out employing the circuit shown in Figure 2(b) [31]. This circuit is specially designed for the monitoring of the on-state voltage of power semiconductors, since during the on-state of the DUT the current

Fig. 2. (a) Internal layout of the power module and (b) circuit implementation of the monitoring system for  $V_{DS}$ .

Fig. 3. Oscilloscope measurement of the on-state voltage measured on the module terminals  $V_{DS}$ , the on-state voltage measured at the input of the ADC  $V_{DS-ADC}$  and circulating current  $I_D$  after turn-on.

source polarizes the two diodes  $D_1$  and  $D_2$  through the power semiconductor. An important fact is that the voltage through the diodes has to be equal, hence both should be matched and thermally-coupled to minimize the error. Moreover, during the off-state, the current cannot flow through the power switch. Hence, the diodes must be able to block the DC-Link voltage to protect the rest of the monitoring system.

The ADC employed for the measurements has 16-bit with input voltage of  $\pm 5\text{V}$ , resulting in a resolution of  $0.15\text{ mV}$ . Its output is transmitted through fiber optics to the digital controller, and sent in a PC via RS-232. Regarding the current, it is measured with a hall-effect current transducer. The digital controller is in charge of synchronizing the PWM and monitoring signals, in order to perform the monitoring when desired.

The monitoring circuit requires a certain settling time in order to get accurate measurements. This is shown in Figure 3, where the drain-to-source voltage of the DUT  $V_{DS}$ , the voltage at the input of the ADC  $V_{DS-ADC}$  and the drain current  $I_D$  measured with an oscilloscope are shown. The measurements were captured with the DUT switching at 1 kHz with Sinusoidal PWM (SPWM) modulation and a unitary modulation index. When the DUT is in the off-state, its drain to source voltage is the DC-Link voltage, while at the input of the ADC  $V_{DS-ADC}$  rises to the saturation voltage of the Op-

Fig. 4. Results of the thermal characterization with DC-currents and  $R_{DS} - T_j$  correlation.

Amp. Furthermore, when the DUT is turned on,  $V_{DS}$  falls to the on-state voltage defined by the circulating current  $I_D$  and the junction temperature. Although an operational amplifier with 9 MHz bandwidth has been employed for the circuit, the current source, the parasitic capacitances of the diodes and the ADC imposes a certain delay between the switch on of the device and the measurement. This minimum on-state time required for monitoring limits both the modulation index and the switching frequency of the DUT, reducing the operating points of the inverter and not taking advantage of the fast switching capabilities of SiC.

### C. Thermal Characterization of the DUT

In order to demonstrate the feasibility of employing the on-state resistance as a TSEP, a thermal characterization test employing DC-currents and an IR camera has been carried out with the prototype. To do this, a sample module has been opened and the soft-gel that covers the active switches and the copper pad removed with a solvent. Afterwards, the module has been painted with high-temperature black paint in order to equalize the emissivity of the surface [32].

The test consisted on forcing DC-currents through the DUT while a constant positive voltage (20 V) is applied to its gate in order to dissipate conduction power losses [32]. This way, a self-heating is generated in the DUT while measurements are acquired [33], such as in a converter during operation. The monitoring system monitors once a second both  $V_{DS}$  and  $I_D$ , while the IR camera monitors the junction temperature.

The measurement results of the correlation between  $R_{DS}$  and  $T_j$  are shown in Figure 4. A curve-fitting has been employed to extract the relation between them. A second-order polynomial has been employed for the correlation, as the one in [29], resulting in the expresion:

$$T_j = a R_{\text{DS}}^2 + b R_{\text{DS}} + c \quad (1)$$

where  $a = -1.4539 \times 10^5$ ,  $b = 1.5067 \times 10^4$  and  $c = -252.1657$  are the curve-fitting parameters.

It is worth to mention that this correlation will be dependent on degradation state of the gate oxide of the DUT. Concretely, significant threshold voltage  $V_{TH}$  shifts have been reported due

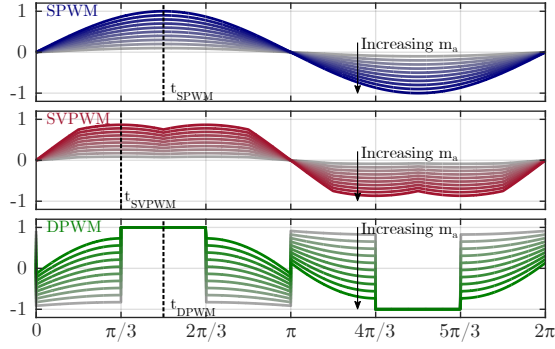


Fig. 5. Fundamental signals of the modulation strategies SPWM, SVPWM and DPWM for different modulation indexes and monitoring instants (dashed lines).

to bias temperature instabilities, caused by trapped charges in the oxide and its interface [34]. In power MOSFETs, the  $R_{DS}$  is mainly composed of three terms: channel, JFET and epitaxial layer resistance. A positive shift in the threshold voltage of a die results in a lower gate overdrive  $V_{GS} - V_{TH}$ , which is further reflected in an increase of the channel resistance [35]. This matter is specially relevant for SiC MOSFETs, since for these devices the channel resistance can make up to 50 % of the total resistance [36].

Although results in [37] show the improvement of the gate oxide ageing of SiC MOSFETs along generations, a change in the temperature coefficients of (1) is expected [38]. In order to overcome this issue, it is proposed in [39] an indicator of the  $V_{TH}$  shift based on the forward voltage of the body diode. This technique could be implemented during maintenance or in an intelligent gate-driver in order to detect the degradation of the gate oxide and carry-out a recalibration.

### III. MODULATION STRATEGIES

#### A. Monitoring with Standard Modulations SPWM and SVPWM

As introduced above, the monitoring system limits the maximum switching frequency that can be achieved. In order to determine the settling time required, the prototype has been tested with both standard SPWM and Space Vector PWM (SVPWM) modulation strategies. Figure 5 shows the SPWM and SVPWM fundamental signals employed to generate the PWM commands in one of the half-bridge branches of the three-phase inverter for various modulation indexes. Here, the modulation index  $m_a$  is defined as:

$$m_a = \frac{2V_1}{V_{DC}} \quad (2)$$

where  $V_{DC}$  is the DC-Link voltage and  $V_1$  is the fundamental peak phase voltage. The signals for the other two branches are obtained by shifting the signal shown.

The digital controller is in charge of synchronizing the measurement command signals and the PWM in such a way that the monitoring is performed during the switching period with the maximum on-state time. Therefore, the measurement

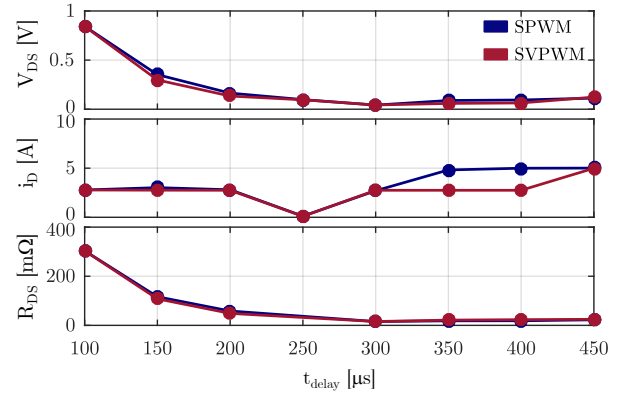


Fig. 6. Measurement results of the on-state voltage  $V_{DS}$ , the circulating current  $I_D$  and the resulting on-state resistance  $R_{DS}$  with SPWM and SVPWM modulations and varying  $t_{delay}$  after turn-on.

instants for each modulation ( $t_{SPWM}$ ,  $t_{SVPWM}$ ,  $t_{DPWM}$ ) are shown in Figure 5, corresponding to the largest on-time of the DUT.

In Figure 6, the results of the measurements with SPWM and SVPWM, 2 kHz switching frequency and 0.95 modulation index are presented. In these tests, the time delay ( $t_{delay}$ ) is defined as the elapsed time between the switch on of the DUT ( $t_{ON}$  in Figure 3) and the measurement acquisition time ( $t_{meas}$ ):

$$t_{delay} = t_{meas} - t_{ON} \quad (3)$$

This parameter is varied from 100 to 450  $\mu s$  in order to determine the minimum delay that ensures an accurate measurement. Figure 6 shows that the current measurement varies from 5 to 0 A during one switching period. This is caused by the intentionally low switching frequency employed for this test relative to the output phase inductance, as shown in Figure 3. The low switching frequency ensures long on-state periods to perform the measurements. As a consequence, the calculated  $R_{DS}$  at  $t_{delay} = 250 \mu s$  has not been plotted in Figure 6 since the current was too low for the calculation. This can also be distinguished in the  $V_{DS}$  measurements for  $t_{delay} = 350$  and  $400 \mu s$ , in which the current in SPWM is higher than in SVPWM, resulting in higher  $V_{DS}$ . However, the measured  $R_{DS}$  is not affected. Furthermore, the low bandwidth of the monitoring system involves a settling time of at least 350  $\mu s$  in order to obtain a stable measured  $R_{DS}$ . This low bandwidth reduces the commutation noise that could alter the measurements. However, it limits the maximum switching frequency to 3 kHz, far below the frequencies reported in literature for SiC-based converters.

#### B. Proposed Modulation Strategy

In order to perform the measurements accurately, the modulation strategy can be modified, with the objective of avoiding the switching of the DUT and hence satisfy the required settling time. For the presented three-phase inverter, this can be obtained by implementing a Discontinuous PWM (DPWM) modulation, in which each switch of the three phase inverter



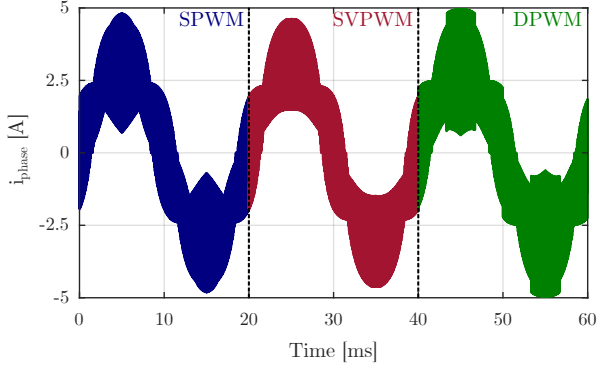


Fig. 7. Simulated output phase current  $i_{\text{phase}}$  of the inverter for SPWM, SVPWM and DPWM modulation strategies, 50 Hz fundamental frequency, 50 kHz switching frequency and unitary modulation index.

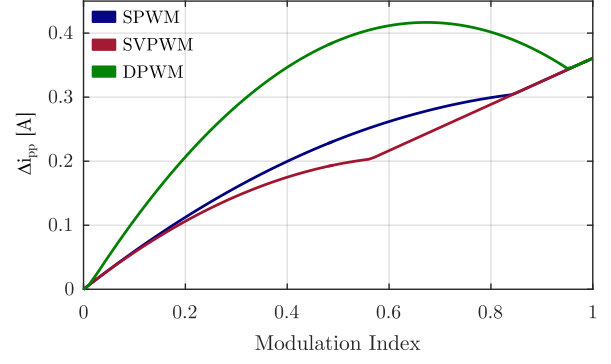
does not commute during 1/6 of the fundamental period. Although this modulation is not novel [40], to the authors knowledge it has not been employed for condition monitoring before.

Figure 5 shows the fundamental signal for this modulation. As can be seen, between  $\pi/3$  and  $2\pi/3$  the signal corresponding to DPWM goes over 1 and hence during this time the switch does not commute. This fact is independent of the modulation index, allowing the CMS to measure at any operating point of the converter.

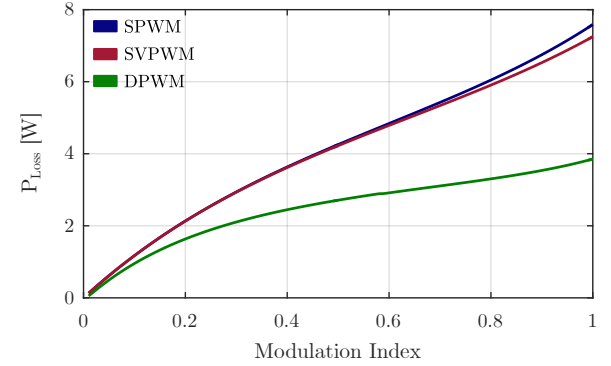
As a consequence of altering the modulation strategy, the output phase voltages are varied and so do the output phase currents. However, since in the proposed modulation a homopolar signal is injected, the fundamental current is not affected. This is illustrated in Figure 7, where the phase current of the prototype for SPWM, SVPWM and DPWM modulations considering 50 Hz fundamental frequency, 50 kHz switching frequency, unitary modulation index and a  $L_{\text{Filter}} = 120 \mu\text{H}$  are shown. A lower  $L_{\text{Filter}}$  has been employed here intentionally to increase the current ripple and show the differences. It can be seen that the current ripple at the switching frequencies is affected, but the fundamental phase current remains the same.

In order to study the high-frequency ripple along the modulation index for each modulation strategy, the system is simulated and the output current extracted. From the later, the fundamental frequency harmonic is removed and the peak-to-peak current ripple  $\Delta i_{\text{pp}}$  is determined. The results are shown in Figure 8(a). It can be seen that the ripple current with DPWM is higher than with the other choices for low- and medium-modulation indexes. Concretely, the increase achieves 85 % with respect to SPWM for  $m_a = 0.15$  and 100 % with respect to SVPWM for  $m_a = 0.56$ . Moreover, for  $m_a > 0.80$  the resulting high frequency ripple current increase is below 40 %, while for  $m_a > 0.94$  it is equal for the three modulation strategies.

As mentioned above and reported in the literature [41], [27], [28], the use of DPWM is particularly targeted for the reduction of power losses. In order to quantify this advantage, the power losses in the semiconductors  $P_{\text{Loss}}$  have been calculated



(a)



(b)

Fig. 8. Comparison of the studied modulation strategies at 50 kHz switching frequency and varying modulation index in terms of (a) peak-to-peak high frequency ripple current  $\Delta i_{\text{pp}}$  and (b) MOSFET power losses  $P_{\text{Loss}}$ .

employing the available datasheet characteristics. Figure 8(b) compares the results for the three studied modulations. While losses in SPWM and SVPWM are similar, a drastic reduction of the power losses is achieved with DPWM. This reduction increases with the modulation index, being higher than 45 % for  $m_a > 0.9$ . The reason is the saturation of the modulation signal during 1/6 of the fundamental period, shown in Fig. 5, which causes that the switch does not switch during that time. Hence, no switching losses are generated, which is highly beneficial when switching at high frequencies.

#### IV. MONITORING RESULTS WITH DPWM

In this section, the results of the implementation of the proposed DPWM in the presented prototype are shown. Figure 9 shows the measured output of the inverter prototype with DPWM implemented: the output phase currents and the drain-to-source voltage of the DUT. The measurements are presented for low, medium and high (0.2, 0.6 and 1) modulation indexes  $m_a$  in Figures 9(a) to 9(c), respectively. It can be seen that the  $V_{\text{DS}}$  of the DUT is held in the DC-Link voltage during 1/6 of the fundamental period and at its saturation voltage during another 1/6. Moreover, the filtered  $V_{\text{DS}}$  reflect the employed modulation signal.

The results of the high-frequency ripple current of the proposed modulation have been compared with those of the

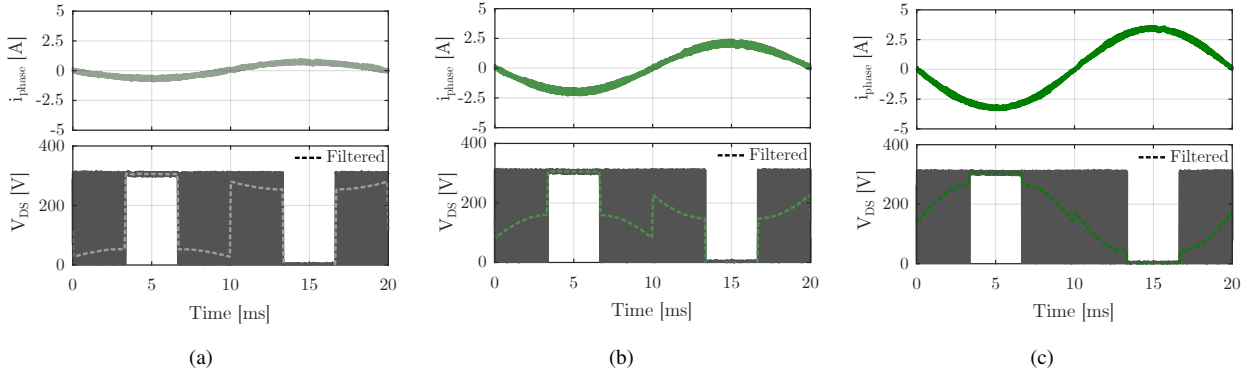


Fig. 9. Inverter output phase current  $i_{\text{phase}}$  and drain-to-source voltage  $V_{\text{DS}}$  of the DUT with DPWM at switching frequency  $f_{\text{sw}} = 50 \text{ kHz}$  and different modulation indexes  $m_a$ : (a)  $m_a = 0.2$ , (b)  $m_a = 0.6$ , (c)  $m_a = 1.0$ .

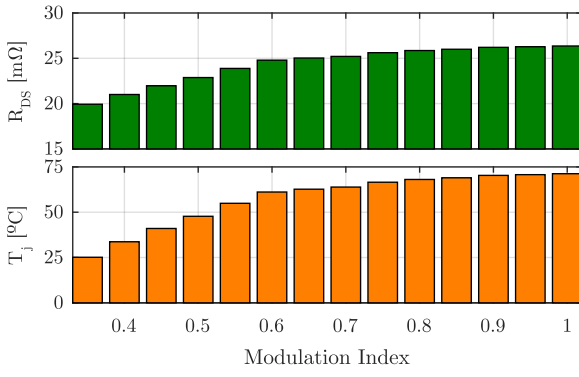


Fig. 10. Measurement results of the on-state resistance  $R_{\text{DS}}$  and temperature estimation  $T_j$  at switching frequency  $f_{\text{sw}} = 50 \text{ kHz}$  and varying the modulation index.

TABLE II  
RIPPLE CURRENT CALCULATION COMPARISON.

| $m_a$ | Calculated $\Delta i_{\text{pp}}$ [A] | Measured $\Delta i_{\text{pp}}$ [A] | Error [%] |
|-------|---------------------------------------|-------------------------------------|-----------|
| 0.2   | 5.79                                  | 5.11                                | 11.72     |
| 0.6   | 10.47                                 | 10.19                               | 2.64      |
| 1.0   | 9.31                                  | 8.93                                | 4.06      |

prototype considering a  $L_{\text{Filter}} = 120 \mu\text{H}$ . Again, a lower  $L_{\text{Filter}}$  has been employed in order to increase the current ripple and hence reduce measurement errors. From the phase current measured with a current probe (Tektronix TCP305-A), the FFT has been calculated, then the terms at the fundamental frequency neglected and finally the current has been reconstructed via inverse FFT to determine the high-frequency peak-to-peak phase current ripple. The measured and calculated results, presented in Table II, shown a maximum error of 11.72 % at low modulation index.

Monitoring tests have also been carried out in order to verify the performance of the monitoring system at different operating points. Figure 10 shows the measurement results of the  $R_{\text{DS}}$  acquired with the device switching at 50 kHz for a modulation index range between 0.35 and 1. The results show how the acquired  $R_{\text{DS}}$  increases with the modulation index due to the higher circulating current, which causes more

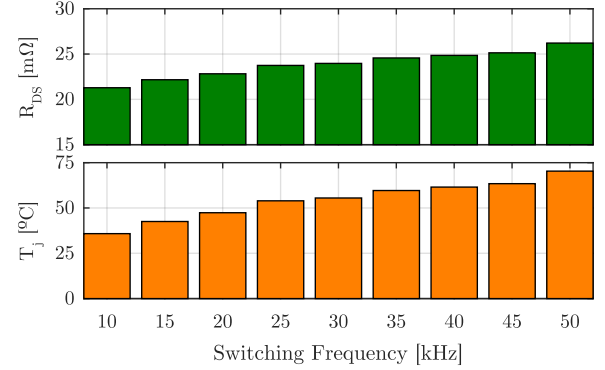


Fig. 11. Measurement results of the on-state resistance  $R_{\text{DS}}$  and temperature estimation  $T_j$  at modulation index  $m_a = 0.95$  and varying the switching frequency.

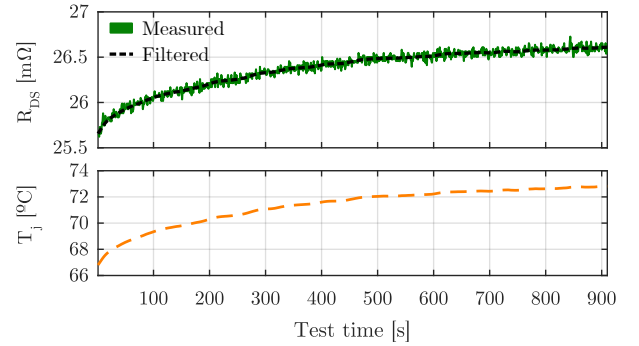


Fig. 12. Measurement results of the on-state resistance  $R_{\text{DS}}$  and temperature estimation  $T_j$  in long-term monitoring test at  $f_{\text{sw}} = 50 \text{ kHz}$  and  $m_a = 0.95$ .

power losses. This is reflected in an increase of the junction temperature, estimated through the correlation presented in (1).

Moreover, in Figure 11, the results of a test in which the switching frequency is varied between 10 and 50 kHz while the modulation index is maintained at  $m_a = 0.95$  are presented. Again, increasing the switching frequency involves higher power losses, resulting in higher measured  $R_{\text{DS}}$  and higher estimated junction temperatures.

Finally, Figure 12 presents the long-term monitoring results of the prototype tested at  $f_{sw} = 50 \text{ kHz}$  and  $m_a = 0.95$ . Here, measurements are acquired once per second, and then translated to temperature. The temperature increase during the test is patent.

## V. CONCLUSIONS

This paper presents a condition-monitoring system based on discontinuous PWM targeted for three-phase inverters operating at high switching frequencies. Employing this modulation, the device does not switch during part of the fundamental period of the inverter. This way, the output of the  $V_{DS}$  monitoring circuit is stable, and measurement accuracy is not compromised. However, power losses and output phase currents are also affected.

An inverter prototype has been designed, and the limitations of the monitoring with regular modulations have been presented. A  $350 \mu\text{s}$  minimum on-state time has been determined for correct measurement, which limits the switching frequency and modulation index of the DUT. The proposed modulation is presented to overcome this issue and compared with the previous modulations in terms of current ripple and power losses. While high-frequency phase current ripple is increased, the power losses are drastically reduced due to the absence of commutation during 1/6 of the fundamental period.

Measurement results are presented with the proposed modulation in an inverter for various operating points. Moreover, based on a thermal characterization test carried out on a sample module, an online estimation of the junction temperature has been carried out.

## REFERENCES

- [1] J. Millan, P. Godignon, X. Perpiñà, A. Perez-Tomas, and J. Rebollo, "A Survey of Wide Bandgap Power Semiconductor Devices," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2155–2163, may 2014.
- [2] J. San-Sebastian, A. Rujas, L. Mir, A. Berasategi, and T. Nieva, "Performance improvements using silicon carbide hybrid IGBT modules in traction application," in *2016 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*. IEEE, nov 2016, pp. 1–6.
- [3] A. Rujas, I. Villar, I. Etxeberria-Otadui, U. Larranaga, and T. Nieva, "Design and experimental validation of a silicon carbide 100kW battery charger operating at 60kHz," in *2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL)*. IEEE, jun 2014, pp. 1–7.
- [4] H. Zhang and L. M. Tolbert, "Efficiency Impact of Silicon Carbide Power Electronics for Modern Wind Turbine Full Scale Frequency Converter," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 21–28, jan 2011.
- [5] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rikken, J. B. Jacobsen, T. Kvisgaard, and J. Landkildehus, "Transitioning to Physics-of-Failure as a Reliability Driver in Power Electronics," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 1, pp. 97–114, mar 2014.
- [6] J. Falck, C. Felgelmacher, A. Rojko, M. Liserre, and P. Zacharias, "Reliability of Power Electronic Systems: An Industry Perspective," *IEEE Industrial Electronics Magazine*, vol. 12, no. 2, pp. 24–35, jun 2018.
- [7] M. Andresen, K. Ma, G. Buticchi, J. Falck, F. Blaabjerg, and M. Liserre, "Junction Temperature Control for More Reliable Power Electronics," *IEEE Transactions on Power Electronics*, vol. 33, no. 1, pp. 765–776, jan 2018.
- [8] X. Perpiñà, L. Navarro, X. Jordà, M. Vellvehi, J.-F. Serviere, and M. Mermet-Guyennet, "Reliability and Lifetime Prediction for IGBT Modules in Railway Traction Chains," *Reliability and Safety in Railway*, no. January, pp. 193–222, 2012.
- [9] U.-M. Choi, F. Blaabjerg, and K.-B. Lee, "Study and Handling Methods of Power IGBT Module Failures in Power Electronic Converter Systems," *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2517–2533, may 2015.
- [10] H. Oh, B. Han, P. McCluskey, C. Han, and B. D. Youn, "Physics-of-Failure, Condition Monitoring, and Prognostics of Insulated Gate Bipolar Transistor Modules: A Review," *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2413–2426, may 2015.
- [11] B. Hu, J. Ortiz Gonzalez, L. Ran, H. Ren, Z. Zeng, W. Lai, B. Gao, O. Alatise, H. Lu, C. Bailey, and P. Mawby, "Failure and Reliability Analysis of a SiC Power Module Based on Stress Comparison to a Si Device," *IEEE Transactions on Device and Materials Reliability*, vol. 17, no. 4, pp. 727–737, dec 2017.
- [12] Y. Avenas, L. Dupont, N. Baker, H. Zara, and F. Barruel, "Condition Monitoring: A Decade of Proposed Techniques," *IEEE Industrial Electronics Magazine*, vol. 9, no. 4, pp. 22–36, dec 2015.
- [13] P. Ghimire, S. Beczkowski, S. Munk-Nielsen, B. Rannestad, and P. B. Thogersen, "A review on real time physical measurement techniques and their attempt to predict wear-out status of IGBT," in *2013 15th European Conference on Power Electronics and Applications (EPE)*. IEEE, sep 2013, pp. 1–10.
- [14] A. Griffo, J. Wang, K. Colombage, and T. Kamel, "Real-Time Measurement of Temperature Sensitive Electrical Parameters in SiC Power MOSFETs," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 3, pp. 2663–2671, mar 2018.
- [15] N. Degrenne, J. Ewanchuk, E. David, R. Boldyrjew, and S. Mollov, "A Review of Prognostics and Health Management for Power Semiconductor Modules," in *Annual Conference of the Prognostics and Health Management Society*, 2015, pp. 1–11.
- [16] S. H. Ali, X. Li, A. S. Kamath, and B. Akin, "A Simple Plug-In Circuit for IGBT Gate Drivers to Monitor Device Aging: Toward Smart Gate Drivers," *IEEE Power Electronics Magazine*, vol. 5, no. 3, pp. 45–55, sep 2018.
- [17] N. Baker, L. Dupont, S. Munk-Nielsen, F. Iannuzzo, and M. Liserre, "IR Camera Validation of IGBT Junction Temperature Measurement via Peak Gate Current," *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 3099–3111, apr 2017.
- [18] U.-M. Choi, F. Blaabjerg, S. Jorgensen, S. Munk-Nielsen, and B. Rannestad, "Reliability Improvement of Power Converters by Means of Condition Monitoring of IGBT Modules," *IEEE Transactions on Power Electronics*, vol. 32, no. 10, pp. 7990–7997, oct 2017.
- [19] M. Denk and M.-M. Bakran, "Health-Monitoring of IGBT power modules using repetitive half-sinusoidal power losses," in *PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, no. May, Nuremberg, Germany, may 2016, pp. 10–12.
- [20] F. Gonzalez-Hernando, J. San-Sebastian, A. Garcia-Bediaga, M. Arias, F. Iannuzzo, and F. Blaabjerg, "Wear-out Condition Monitoring of IGBT and MOSFET Power Modules in Inverter Operation," *IEEE Transactions on Industry Applications*, vol. PP, no. c, pp. 1–1, 2019.
- [21] F. Stella, G. Pellegrino, E. Armando, and D. Dapra, "On-line temperature estimation of SiC power MOSFET modules through on-state resistance mapping," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, oct 2017, pp. 5907–5914.
- [22] M. Guacci, D. Bortis, and J. W. Kolar, "On-State Voltage Measurement of Fast Switching Power Semiconductors," *CPSS Transactions on Power Electronics and Applications*, vol. 3, no. 2, pp. 163–176, jun 2018.
- [23] U.-M. Choi, I. Vernica, and F. Blaabjerg, "Asymmetric Pulse Width Modulation for Improving the Reliability of Motor Drive Inverters," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, sep 2018, pp. 6430–6435.
- [24] A. Isidoril, F. M. Rossi, F. Blaabjerg, and K. Ma, "Thermal Loading and Reliability of 10-MW Multilevel Wind Power Converter at Different Wind Roughness Classes," *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 484–494, jan 2014.
- [25] B. Wang, "Review of Power Semiconductor Device Reliability for Power Converters," *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 2, pp. 101–117, jun 2017.
- [26] M. Aguirre, P. Madina, J. Poza, A. Aranburu, and T. Nieva, "Analysis and comparison of PWM modulation methods in VSI-Fed PMSM drive systems," in *2012 XXth International Conference on Electrical Machines*. IEEE, sep 2012, pp. 851–857.



- [27] Nho-Van Nguyen, Bac-Xuan Nguyen, and Hong-Hee Lee, "An Optimized Discontinuous PWM Method to Minimize Switching Loss for Multilevel Inverters," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 3958–3966, sep 2011.
- [28] H. J. Lee, A. Yoo, C. Hong, and J. Lee, "A carrier-based adjustable discontinuous PWM for three-phase voltage source inverter," *2015 IEEE Energy Conversion Congress and Exposition, ECCE 2015*, no. 1, pp. 2870–2875, 2015.
- [29] X. Han and M. Saeedifard, "Junction temperature estimation of SiC MOSFETs based on Extended Kalman Filtering," in *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, vol. 2018-March. IEEE, mar 2018, pp. 1687–1694.
- [30] N. Degrenne and S. Mollov, "Experimentally-Validated Models of On-State Voltage for Remaining Useful Life Estimation and Design for Reliability of Power Modules," in *CIPS 2018; 10th International Conference on Integrated Power Electronics Systems*, Stuttgart, Germany, mar 2018, pp. 476–481.
- [31] S. Beczkowski, P. Ghimre, A. R. de Vega, S. Munk-Nielsen, B. Rannestad, and P. Thogersen, "Online Vce measurement method for wear-out monitoring of high power IGBT modules," in *2013 15th European Conference on Power Electronics and Applications (EPE)*. IEEE, sep 2013, pp. 1–7.
- [32] F. Gonzalez Hernando, J. SanSebastian, M. Arias, and A. Rujas, "Thermal Characterization of Multichip Power Module," in *2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe)*, Riga, Latvia, sep 2018, pp. 1–9.
- [33] Y. Avenas, L. Dupont, and Z. Khatir, "Temperature Measurement of Power Semiconductor Devices by Thermo-Sensitive Electrical Parameters A Review," *IEEE Transactions on Power Electronics*, vol. 27, no. 6, pp. 3081–3092, jun 2012.
- [34] H. Luo, F. Iannuzzo, and M. Turnaturi, "Role of Threshold Voltage Shift in Highly Accelerated Power Cycling Tests for SiC MOSFET Modules," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. PP, no. c, pp. 1–1, 2019.
- [35] J. Ortiz Gonzalez and O. Alatise, "Bias temperature instability and condition monitoring in SiC power MOSFETs," *Microelectronics Reliability*, vol. 88–90, no. June, pp. 557–562, sep 2018.
- [36] T. Aichinger, G. Rescher, and G. Pobegen, "Threshold voltage peculiarities and bias temperature instabilities of SiC MOSFETs," *Microelectronics Reliability*, vol. 80, no. November 2017, pp. 68–78, jan 2018.
- [37] A. J. Lelis, R. Green, D. B. Habersat, and M. El, "Basic Mechanisms of Threshold-Voltage Instability and Implications for Reliability Testing of SiC MOSFETs," *IEEE Transactions on Electron Devices*, vol. 62, no. 2, pp. 316–323, feb 2015.
- [38] J. O. Gonzalez and O. Alatise, "Impact of the Gate Oxide Reliability of SiC MOSFETs on the Junction Temperature Estimation Using Temperature Sensitive Electrical Parameters," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, sep 2018, pp. 837–844.
- [39] J. A. O. Gonzalez and O. Alatise, "A Novel Non-Intrusive Technique for BTI Characterization in SiC mosfets," *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5737–5747, jun 2019.
- [40] A. Hava, R. Kerkman, and T. Lipo, "A high-performance generalized discontinuous PWM algorithm," *IEEE Transactions on Industry Applications*, vol. 34, no. 5, pp. 1059–1071, 1998.
- [41] M. Z. Sujod, I. Erlich, and S. Engelhardt, "Improving the Reactive Power Capability of the DFIG-Based Wind Turbine During Operation Around the Synchronous Speed," *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 736–745, sep 2013.



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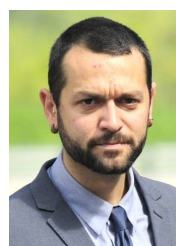
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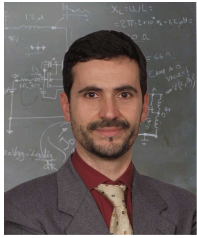
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